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Economic, policy, and social trends and challenges of introducing oilseed and pulse crops into dryland wheat cropping systems

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ABSTRACT

The productivity of semi-arid, cereal-based agroecosystems is inherently limited by water and nutrient availability, with water limitations expected to be exacerbated by climate change. While previous studies have identified agronomic, economic, and environmental benefits of rotating oilseed, pulse, and cover crops with cereals for mitigating the effects of increasing temperatures and water shortages, the successful integration of alternative crops into cereal based systems is contingent upon economic, social, and policy conditions. This paper analyses the historical spatial and temporal trends in crop diversification in three distinct cropping regions, including the Canadian prairies, Australian wheat belt, and the inland Pacific Northwest USA (iPNW). The first objective was to identify key sociological, economic, and policy drivers that corresponded with historical crop intensification and diversification in Canada and Australia over the last 50 years. The second objective was to identify key economic, policy, and social constraints that have historically limited intensification and diversification in the iPNW, a cereal-dominated region. In Canada and Australia, public policy played a critical role in the adoption of alternative crops through investments in research and boundary-spanning agencies, as well as extension and grower-led efforts. Policies also provided incentives for market development and risk management strategies. Grower perceptions of risk, the ability to utilize existing resources and knowledge, and access to markets were important social considerations for crop diversification. Given the competitiveness of wheat in the iPNW, the largest opportunities for diversification in the iPNW would be provided by (1) the adoption of a crop rotation approach to the economics that capture relative commodity prices, yield stability, and the effects of alternative crops on subsequent wheat performance, (2) the transition away from coupled crop insurance to income-supported, whole farm risk management, and (3) the establishment of multi-commodity groups that replace single crop commodity commissions in the interest of market-driven crop diversification.

1. Introduction

Cereals comprise most of the world's cropland (FAOSTAT, 2016) and provide about half of the global dietary energy (Ray et al., 2013; FAOSTAT, 2016). Agricultural trends indicate that wheat (*Triticum aestivum*) makes up 30% of the harvested cereal area since 1961 (FAOSTAT, 2016) and is extensively grown in semi-arid regions (defined here as less than 530 mm of precipitation) (Koohafkan and Stewart, 2008). For the last 50 years, while global cereal and pulse area has remained fairly constant (785 and 86 million hectares, respectively), oilseed area nearly tripled from 131 to 324 million hectares—altogether cereals, pulses, and oilseeds comprising up to 90% of cropland. While the increase of oilseed area prior to the early 1990s was due to an expansion of agricultural cropland

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globally, the recent rise in oilseed area may be attributable to the intensification, as defined by the reduction in annual fallow periods, and diversification of cerealbased system, particularly with soybean (*Glycine max*) and canola (*Brassica napus*) (FAOSTAT, 2016). The global increase in oilseed production has supported dietary shifts towards increased vegetable oil-based calorie consumption (Drewnowski, 2000).

Agronomic critiques of cereal monoculture systems have often focused on their ecological instability, high demand for inputs, and low resource use efficiencies (Matson et al., 1997; Tilman, 1999). Crop diversification is a strategy to increase resilience in agro-ecosystems (Lin, 2011), and crop diversity may be particularly important to stabilize systems vulnerable to a changing climate (Altieri et al., 2015). While crop diversification can refer to multiple crop species grown in temporal sequences and/or spatial associations (Kassam et al., 2012), much attention has been devoted to diversified crops in rotation as an alternative to wheat monocultures, which is the focus of this paper. Many long-term studies and reviews have demonstrated the agronomic (Johnston et al., 2005; Kirkegaard et al., 2008; Hansen et al., 2012; Cutforth et al., 2013; Angus et al., 2015), economic (Entz et al., 2002; Zentner et al., 2002, 2004), and environmental (Zentner et al., 2004; Gan et al., 2011; Davis et al., 2012) benefits of diversified crop rotations. Crop diversification alone does not necessarily solve financial and yield risks faced by farmers (Zentner et al., 2001, 2002; Robertson et al., 2010; Kirkegaard et al., 2016).

Wheat farmers have historically faced multiple economic, social, and environmental conditions that threaten the stability of their cropping systems. For example, in the USA, price volatility along with production risks have led to a decline in federal crop revenue guarantees for wheat since 2013 (USDA RMA, 2016a) with expected increases in price-related government payments in 2016 (USDA ERS, 2016). From 2002 to 2012, younger and new farmers owned proportionately less and increasingly rented more land than established growers amidst rising cash rents (Katchova, 2016), and the growth in farm debt is expected to exceed the rise in farm assets. Rising costs are particularly a problem when the use of current technology has narrowed the exploitable gap between actual and water-limited yields, highlighting the need for new innovation to increase productivity and reduce economic risks (van Rees et al., 2014). Wheat producers also face the uncertainties of climate change, which may reduce crop production depending upon the extent of warming at critical growth stages and nutrient stress (Rosenzweig et al., 2014; Asseng et al., 2015).

While crop diversity may provide viable agroecological solutions to monoculture-based problems, current economic, policy, and social conditions affect the capacity and willingness of growers to change their cropping practices. The well-documented, long term trends of cereal system diversification and intensification in Canada and Australia provide an opportunity to identify key economic, social, and policy drivers that correlate to historical cropping trends. In contrast, crop diversification in the inland Pacific Northwest (iPNW) of the USA has not been as extensive over the same time period, and so the second objective is to identify major constraints that have limited crop diversification in the iPNW and to identify current drivers of recent increases in crop diversification. The rationale for making a global comparison was two-fold. First, the iPNW growers are expected to face future environmental, economic, and market challenges to the wheat monocultures, which may be partially mitigated by increased crop diversification. Second, similar alternative crops have been identified in each of these three wheat-based regions; and therefore, the Canadian and Australian experience and record could help identify economic, social, and policy constraints and drivers relevant to diversification and intensification in the iPNW.

2. Methodology

2.1. Historical cropping trends

2.1.1. Canada

Annual data were collected for area under summer fallow (pertaining to land not cropped for an entire growing season, hereon referred to as “annual fallow”), seeded to grain crops, harvested, crop yield, and production in Alberta, Saskatchewan, and Manitoba from Statistics Canada for 1908 to 2015 period (Canada Statistics, 2015). Data were listed by small area data regions from 1977 to 2015, which were converted to soil type-based agroecological areas according to a previous study (Zentner et al., 2002). The brown soil zone is associated with the semi-arid region of the Canadian Prairies, whereas the grey or black soil zones are associated with the sub-humid region and dark brown soil encompassing the transition region (Anderson, 2010). Cereals were categorized as the sum of barley (*Hordeum vulgare*), oats (*Avena sativa*), and wheat; pulses included chickpea (*Cicer arietinum*), field pea (*Pisum sativum*), and lentil (*Lens culinaris*).

2.1.2. Australia

To document Australia’s cereal and pulse production between 1861 and 2015, data were collected from Australian censuses and commodity statistics (ABARES 1977–2015, FAOSTAT 1961–1976, and Australia Yearbooks 1861–1961). The data of interest were area harvested, yield, and production of crop types. Cereals were categorized as the sum of barley, oats, and wheat, whereas pulses included narrow-leaf lupin (*Lupinus angustifolius*), chickpea, dry field pea, dry bean, and lentils based on available data. Production data were then listed by regions from 1993 to 2015, including North (Queensland), South (Victoria, South Australia, and Tasmania), and West (Western Australia) regions. New South Wales was listed separately as the state includes agroecological zonal transition between the North and South regions (Kearns and Umbers, 2010; Hooper and Levantis, 2011a,b,c,d,e,f,g,h,i; Hooper et al., 2011a,b,c,d; Edwards et al., 2012). Cereals were categorized as the sum of barley and wheat; pulses as the sum of lupins, chickpeas, mungbeans (*Vigna radiata*), faba beans (*Vicia faba*), and dry field pea; and oilseeds as canola (ABARES 1993–2015). Sorghum (*Sorghum bicolor*) was included as a summer cereal crop in Queensland, but was analyzed separately from the winter cereals. The relationship between annual rainfall and canola percentage of cropland in South and West regions was fit with a linear regression, using data provided in the ABARES benchmark reports for the Grains Research and Development Corporation (GRDC) (Kearns and Umbers, 2010; Hooper and Levantis, 2011a,b,c,d,e,f,g,h,i; Hooper et al., 2011a,b,c,d; Edwards et al., 2012) and calculated with the stats package in R (R Core Team, 2016).

2.2. Canadian and Australia investments in research and development

Trends in Canadian and Australian research funding were examined to determine the relationship and importance of investments in research to alternative crop adoption. In Canada, research funding for field pea and lentil crops in the Canadian Prairies was obtained for 2001 to 2011 from Carew et al. (2013). Research funding for canola was adapted from Gray et al. (2001) and Brewin and Malla (2013) for 1961 to 1999. In Australia, research funding for canola and pulse crops (field pea and chickpea) by GRDC investments were calculated as the sum of project funding dedicated to individual crops as listed in the GRDC Annual Report Appendix for projects. Prior to 1999, GRDC investments were adapted from Cullen (2012). To avoid spurious correlations, crop funding and production time series data was transformed using the first difference approach, where year-to-

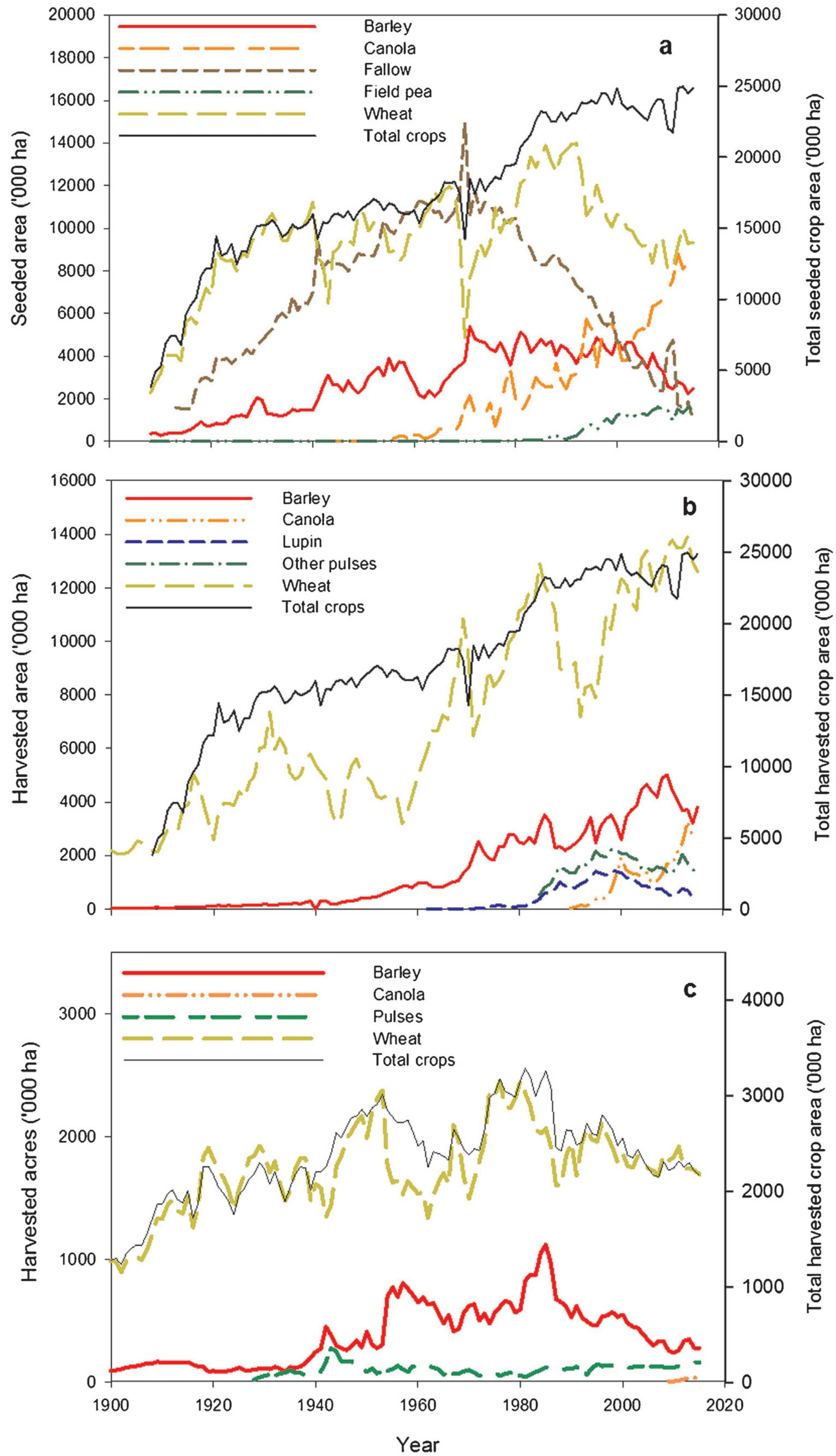

Fig. 1. Area of various crops (a) seeded to various crops in the Canadian prairie provinces of Alberta, Saskatchewan, and Manitoba. [Data Source: Statistics Canada (Statistics Canada, 2016)], (b) harvested in Australia. Total crops included wheat, barley, oats, canola, flax (Canada), chickpea, lupin (Australia), lentil, and field pea (Data Source: ABARES 1977–2015, FAOSTAT 1961–1976, and Australia Yearbooks 1861–1961), and (c) harvested area in the states of Washington, Idaho, and Oregon, USA (Data Source: USDA NASS Quickstat database).

year differences (year 2-year 1, year 3-year 2, etc.) were calculated for each data series. Correlations were then determined on the transformed data series, independent of factors impacting both time series data, using Pearson correlation coefficients in R (R Core Team, 2016).

Trends in Canadian and Australian research publications were examined with bibliometrics to evaluate the relationship and importance of advancement in scientific knowledge to alternative crop adoption. The Web of Science™ database (Thomson Reuters, New York) was utilized to quantify publications written in Canada and Australia on canola and selected pulse crops from 1864 to 2015. Canola was selected since it is the major oilseed grown in Canada and Australia. Field pea was selected for Canada because of its prevalence in the Canadian prairies. Chickpea was selected for Australia due to its continued expansion during the last decade. Keyword searches included ((canola OR rapeseed OR (brassica AND napus)) AND (canada OR manitoba Or saskatchewan OR alberta)); ((pea OR (pisum AND sativum)) AND (canada OR manitoba Or saskatchewan OR alberta)); and ((canola OR rapeseed OR (brassica AND napus)) AND australia); and ((chickpea OR (cicer AND arietinum)) AND australia). Search results were individually assessed for relevance. Correlations between selected crop funding and citations were determined with Pearson correlation coefficients in R on first difference transformed data; using the approach described for crop funding (R Core Team, 2016). The data were then analyzed for common themes in the body of literature; and data were categorized by the identified themes.

2.3. Historical cropping trends for the inland Pacific Northwest

`For the iPNW, annual data were collected for area harvested, yield, and production of crop types in Washington, Idaho, and Oregon, from USDA NASS QuickStat database for 1869 to 2015. The potential environmental constraints were assessed by disaggregating data according to agroecological classes, including the grain-fallow, transition, and annual cropping areas. The agroecological class data were derived from the United States Department of Agriculture National Agricultural Statistics Service (USDA NASS) Cropland Data Layer for 2007 to 2014 (Huggins et al., 2014).

2.3.1. Economic constraints to crop diversification in iPNW: rotational sensitivity analyses

The effects of economic and policy conditions on the profit margins were assessed for diversified wheat rotations in comparison to traditional wheat-based rotations. Rotational economics were assessed using two Washington State University enterprise extension tools: Enterprise Budgets: Wheat and Canola Rotations in Eastern Washington Low Rainfall (<12″) Region and Intermediate Rainfall (12–16”) Region (Connolly et al., 2015a,b). Baseline canola and wheat policy scenarios were established using USDA Risk Management Agency (RMA) crop insurance cost estimator and county level target yields as well as prices for 2013 revenue protection (USDA RMA, 2016b). Adams County, Washington, target levels were used in the Low Rainfall budget; while Columbia County, Washington, target levels were used in the Intermediate Rainfall budget. Under variable output price and yield scenarios, total operational costs were assumed to remain constant. By conducting sensitivity analyses, the variable effects of variable winter wheat yields, substitution crop yields, commodity prices, and lease agreements on grower profit. Profit was calculated as total revenue minus total costs. The rotations of interest were winter wheat-fallow-winter wheat-fallow versus winter wheat-fallow-winter canola-fallow in the low rainfall zone, and winter wheat-spring wheat-fallow versus winter wheat-spring canola-fallow in the intermediate rainfall zone. The oilseed rotation profit was subtracted from the cereal rotation profit to determine relative rotation profitability under the variable conditions.

2.3.2. Social constraints to crop diversification in iPNW: survey of iPNW growers

Survey data was utilized to assess grower perceptions of crop diversification. Between December 2012 and March 2013, a mail survey of wheat farmers operating in the iPNW was undertaken within an interdisciplinary research project (*USDA-NIFA Regional Approaches to Climate Change*, REACCH). A survey instrument was administered to focus on agricultural practices, perceptions of risk associated with climate change, and producers' views of adaptive strategies and was sent to a simple random sample of 1988 unique farm operations. After four mailings and a reminder postcard, employing the Dillman method for data collection (Dillman et al., 2008), a total of 900 completed surveys were obtained and included in the analysis. The margin of sampling error was +/− 3 percentage points at a 95% confidence level. The final response rate was 46.2% (AAPOR, 2011).

This paper analyses several specific topics from the survey, including agroecological classifications (AEC) based on percentage of cropland under fallow, farmers' perception of environmental and economic risk associated with climate change projections, and their perceived changes in crop rotation based on anticipated climate changes. The survey measures were structured as Likert-scale items and designed in response to a projected climate change model for the region. Data analysis of the REACCH 2013 survey data was conducted using SAS 9.4 statistical software (SAS Institute, Cary, NC), and the SAS SURVEY FREQ procedure was used to calculate response frequencies and compute the variance estimates.

Attendees (n = 58) of Washington's Oilseed Crop Production Workshop in Odessa, Washington, were surveyed on 24 January 2012, using TurningPoint clickers (Turning Technologies, LLC, Youngstown, Ohio). Attendees (n = 103) were surveyed again on 23 January 2013, at the Oilseed Production and Marketing Conference in Kennewick, Washington. Attendees were asked about occupation, experience with growing oilseeds, likelihood of growing canola in the future, perceived limitations of growing canola, perceived rotational benefits of growing canola, and observed increases in winter wheat yields with canola in rotation. Attendee response frequencies were tabulated in Microsoft Excel.

3. Results and discussion

3.1. Historic cropping trends in Canada, Australia, and the iPNW

For more than 100 years, Canadian, Australian, and iPNW grain systems have been cereal-based (Fig. 1). Wheat-based production has been sustained by utilizing breaks in the cropping sequence, with pasture, fallow periods, or alternative cereal, oilseed and pulse crops (Carlyle, 1997; Seymour et al., 2012; Angus et al., 2015; Malik et al., 2015). However, from the 1960s (Canada) and 1990s (Australia), pulse and oilseed crops expanded rapidly across cropping systems, but have remained a minor importance in the iPNW. It should be noted, for the purposes of this article, the term "summer fallow" is avoided due to conflicting meanings among the regions. Therefore, we refer to "annual fallow" as the absence of a crop during the growing season.

3.1.1. Canada

Canadian wheat acreage grew steadily in Alberta, Saskatchewan, and Manitoba, at the start of the 20th century (Fig. 1a), paralleling the expansion (or extensification) of cropland until 1950. Canadian wheat boards provided market risk management to growers as the sole buyer of wheat, marketer of cereals, and the

source of price stability within their jurisdictions until 2012 (U.S. Congress Office of Technology Assessment, 1989; Schmitz et al., 1997). Trends in annual fallow were driven by Canadian agricultural policy: (1) the practice of annual fallow increased throughout Canada in the early 1900s partly as a means to enhance area-based delivery quotas set by the Canadian Wheat Board, and (2) a noticeable decrease in wheat production occurred in the 1970, coupled with an increase in annual fallow area, in response to public policy in which the government made producer payments to set aside land through the Lower Inventories for Tomorrow Program (Carter et al., 1989; Carlyle, 1997).

Major efforts to diversify crops with oilseed and pulse crops in Canada were in response to the global wheat glut of the 1980s, which resulted in a decline in prices due to an oversupply of wheat (Carter et al., 1989; U.S. Congress Office of Technology Assessment, 1989). In Canada, the percentage of the total cropland dedicated to wheat production has declined with time. As total agricultural land peaked in 1985, subsequent diversification has been the result of the intensification of crop rotations through the reduction of annual fallow. Intensification was made possible on the production side through fertilizer and chemical weed management through the adoption of soil conservation practices, and on the demand side through market expansion for oilseeds and pulses (Carlyle, 1997; Padbury et al., 2002; Zentner et al., 2002). In the 1990s, canola surpassed barley as the second most seeded grain crop, which reached a maximum in 2014 and now constitutes 86% of area seeded to wheat. By 2015, canola, field pea, wheat, and barley cropland each encompassed more area than annual fallow (e.g. no crop harvested for a growing season). Canada has since become the world's largest exporter of canola, field pea, and lentils (FAOSTAT, 2016).

Cropping trends across Canada's soil type-based agroecological areas are presented as a continuation of previous work performed by Zentner et al. (2002), who analyzed data from 1977 to 1997. From 1977 to 2015, the area seeded to cereals ranged from 44 to 75% of grain cropland, which fluctuated more in the grey/black soil zone of the sub-humid region and least in the brown soil, semi-arid region (Fig. 2a). However, differences in percentages among the regions have diminished since 2003. The production of canola (Fig. 2b) increased in all regions but at different times and is more prevalent in the sub-humid areas: sub-humid (grey/black zone) prior to 1977; semi-arid transition (dark brown), 1977; and semi-arid (brown), 1993. The prevalence of pulse crops was similar in the 1990s among the various regions (Fig. 2c). However, pulse crop acreage increased more dramatically in 1999 within the drier brown and dark brown zone, but has remained less than 10% in the

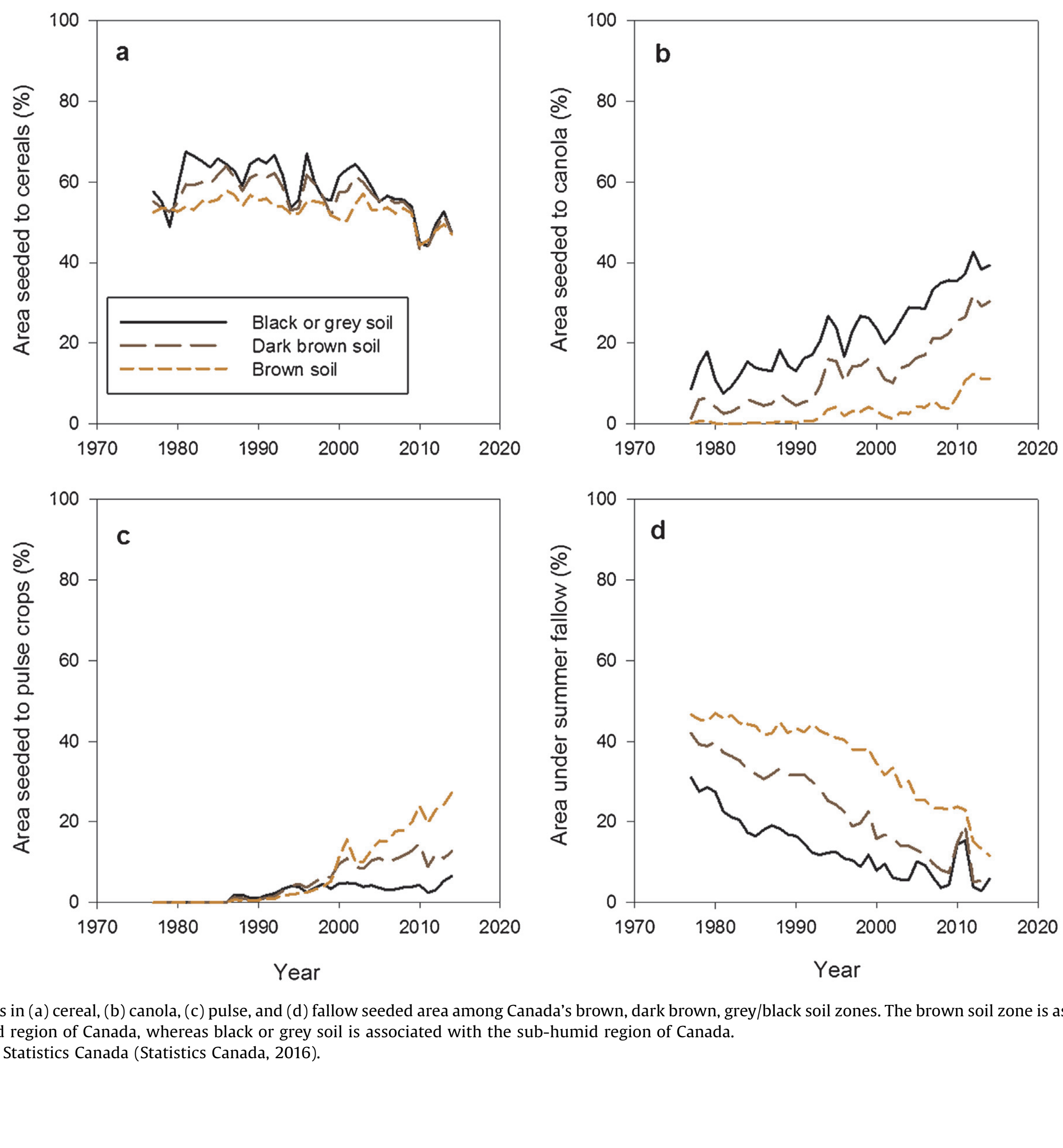

Fig. 2. Trends in (a) cereal, (b) canola, (c) pulse, and (d) fallow seeded area among Canada's brown, dark brown, grey/black soil zones. The brown soil zone is associated with the semi-arid region of Canada, whereas black or grey soil is associated with the sub-humid region of Canada.
Data source: Statistics Canada (Statistics Canada, 2016).

wetter grey/black zone. Annual fallow decreased among all regions, and less than 30% of sub-humid region in 1978; semi-arid transition in 1992; and semi-arid region in 2005 (Fig. 2d).

3.1.2. Australia

Australia's harvested wheat area grew steadily as cropland expanded from 1860 to 1930, 1957 to 1984, and 1992 to 2013, whereas barley area increased from 1940 to 2008 (Fig. 1b). Similar to Canada, the Australian wheat board provided market risk protection to growers as the sole buyer of wheat, marketer of cereals, and the source of price stability within their jurisdictions until 1999 (U.S. Congress Office of Technology Assessment, 1989; Schmitz et al., 1997. However, unlike Canada, mixed crop-livestock operations dominate Australia's cropping systems (Bell et al., 2014), and relatively low wool prices have led to recent increases in cropping intensity (defined in Australia as percentage of farm cropped) across mixed crop-livestock and high rainfall zones (Kirkegaard et al., 2011; Bell and Moore, 2012).

The introduction of wheat quotas in the 1960s, in addition to the global wheat glut of the 1980s, largely stimulated alternative crop research (Colton and Potter, 1999). Lupins were introduced in 1968 and expanded until 1999, at which time lupin area declined as other pulses continued to increase. Canola acreage rapidly increased from 1990 to 2000, followed by a decline in 2004. Canola area has since recovered and reached a maximum in 2013. Australia has become the leading exporter of narrow-leaf lupin and second largest exporter of canola, chickpeas, and lentils, and fourth largest exporter of field pea (FAOSTAT, 2016).

While wheat area has continued to expand in Australia with the proportion of farm area that is cropped increasing since 1975 (Bell and Moore, 2012), the percentage of total cropland dedicated to wheat declined throughout the 1980s and has since remained constant. And so, the increase in alternative crops has occurred partly at the expense of wheat expansion, as well as a decrease in leguminous pasture frequency and extent (Kirkegaard et al., 2011). However, during the Millenium drought of the 2000s, crop diversity declined due to the risk caused by late sowing rains, low spring rainfall, and high spring temperatures in southern systems (Cai et al., 2012; Kirkegaard et al., 2016). Recent attention has returned to the benefits of perennial pastures (Bell et al., 2014) and short fallow as a means to enhance yields under drier conditions in the 300–400 mm rainfall zone (Oliver et al., 2010).

The Australian cropping systems are more complex than Canada and the iPNW, largely because of the predominance of integrated crop-livestock systems (Bell and Moore, 2012). Additionally, pastoral system and crop specialist also exist (Kirkegaard

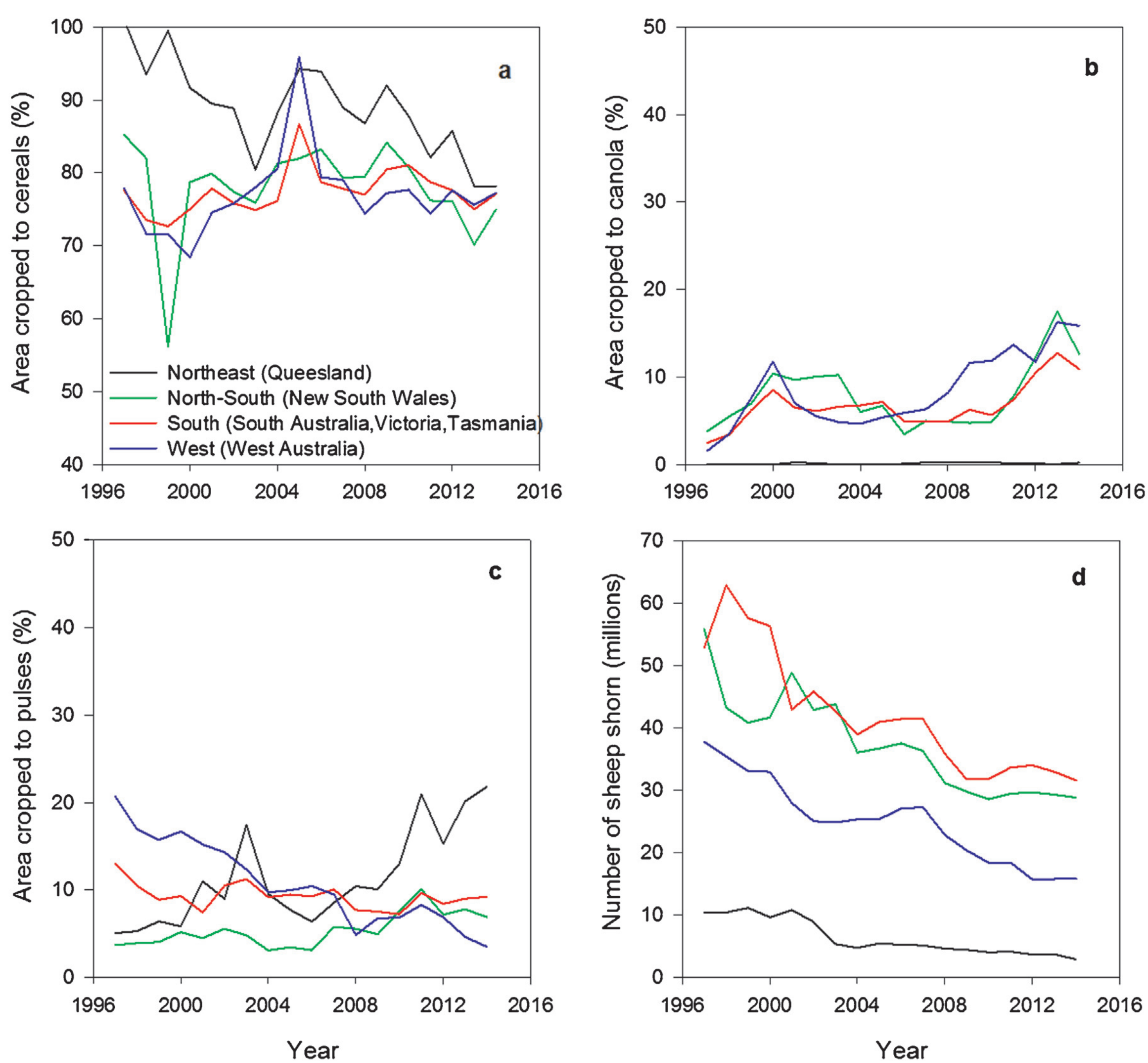

Fig. 3. Trends in (a) cereal, (b) canola, (c) pulse, and (d) sheep numbers in four Australian regions. Queensland lies in northeastern region; New South Wales in transition between north and south; South Australia, Victoria, and Tasmania in the south; and Western Australia in the west.
Data source: ABARES (ABARES, 2015).

et al., 2011), which makes a direct comparison to iPNW difficult. Nevertheless, three primary regions in Australia encompass the northeastern, southern (or central), and southwestern areas of the wheat-belt in Australia, which have distinctly different cropping trends (Fig. 3). In the northeastern region (Queensland), the precipitation pattern is summer-dominant, and sorghum production makes up a third of cereal grains and is grown in summer instead of winter like other grains. For livestock specialists, wool production has declined in recent years, while meat production has increased. On mixed-livestock farms, the proportion of the cropped farm area has remained the same (Bell and Moore, 2012), except in Southeast Queensland and Northeast New South Wales, in which the average percentage of farm area cropped decreased from 2008 to 2014 (Umbers et al., 2015). Chickpeas are the primary break crop in rotation with cereal, and the extent has increased in recent years. In contrast to the north, the southern, central states (Victoria, South Australia, and Tasmania) are characterized by a winter-dominated precipitation pattern. Wheat and barley cropland has expanded in these states within the last 20 years, while canola has become an important break crop. However, pulse area has remained constant, and comprises field pea, lentils, faba bean, lupins, and chickpeas. In the early 1990s, field peas made up half of the pulse area, but have declined in recent years as faba beans have expanded. Lentil area has increased rapidly in South Australia as well since 1996. In New South Wales, the cropping system transitions from southern winter-crop systems with equi-seasonal rainfall to summer dominant systems on clay soils where summer and winter crops are grown on stored soil water on an opportunistic basis according to water availability. Overall, New South Wales, which bridges the transition between the North and the South (Ryan and Kirkegaard, 2012), is generally characterized by uniform precipitation patterns (Bell and Moore, 2012). As a result, while cereal, canola, and wool production in New South Wales has followed similar trends as the southern states, the expansion of chickpea cropping, in addition to the presence of sorghum, resembles trends in Queensland due to similarities in clay soils and summer-dominant rainfall found in northern New South Wales. Lastly, Western Australia, dominated by winter-precipitation, has experienced similar trends in wheat, barley, canola, and wool as the southern states. However, lupins, which constitute 90% of the pulse area, has declined significantly within the last decade (Seymour et al., 2012). Altogether, trends in break crop areas are subject to changes according to sowing opportunities, autumn precipitation, and stored water as the oilseed and grain pulse break crops become more risky with late sowing and less reliable precipitation favoring cereals (Kirkegaard et al., 2016), however the broad trends of increasing diversity up to and beyond the Millenium drought are evident.

3.2. Canadian and a Australian investments in research and development

The effectiveness of public investment in research, development, and extension to leverage and promote agriculture

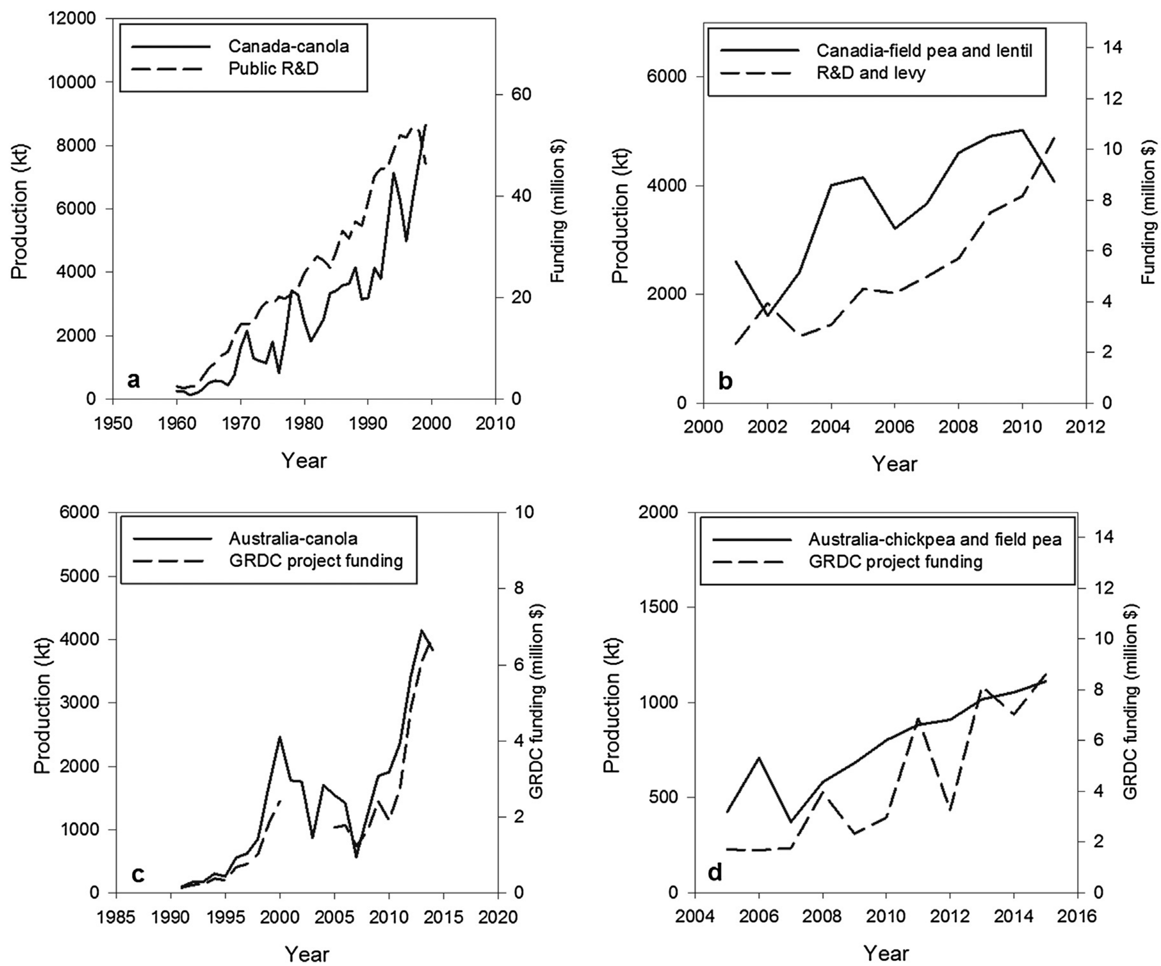

Fig. 4. Trends in funding for research and development and Canada's production of (a) canola and (b) field pea and lentil and Australia's production of (c) canola and (d) field pea and chickpea.
Data sources: (Gray et al., 2001; Carew et al., 2013).

productivity is recognized in Canada (Brewin and Malla, 2013) and Australia (Sheng et al., 2011). Therefore, trends in national investments in research and development were analyzed in relation to the adoption of alternative crops in Canadian and Australian wheat-based cropping systems. Despite increases in both funding and expansion of alternative crops, gains in canola production were only correlated with incremental increases in research and development funding by the GRDC in Australia (r = 0.67, p-value = 0.002) (Fig. 4c). There was no direct relationship between the growth of funding and production of specified pulse crops in Australia or either crops in Canada (Fig. 4a, b, d). A high correlation between research funding and alternative crop production may be expected since a portion of the research funding was supported by grower levies, however funding patterns do not preclude the possibility of public investments to supporting fledging industries or making up only a fraction of total investments.

Likewise, the focus on alternative crops in research publications increased with time, where publications preceded the growth in alternative crop production. However, year-to-year increases in research deliverables were also only positively correlated with incremental increases in Australia canola production (r = 0.42, p-value = 0.05) (Fig. 5c), but unrelated to pulse crops in Australia or either crops in Canada (Fig. 5a, b, d). Therefore, we cannot conclude that investments in research deliverables necessarily had a direct impact on alternative crop production. Though it is tempting to relate the growth of research and development investment/output with production, any conclusion regarding a direct relationship would be an overstatement.

Four common themes were identified in the research deliverables, including breeding and genetics, crop management and protection, cropping systems and rotation, and end-use. In Canada, 53% of the canola papers published between 1943 and 2015 retrieved from the Web of Science™ database were dedicated to crop management and protection; 22%, breeding and genetics; 13%, cropping systems and rotation; and 12%, end-use. In comparison, a greater proportion of the Australian papers published were focused on canola crop management and protection (63%) and the role of canola within cropping systems and rotations (18%), whereas 9% of the studies were written about either breeding and genetics or end-use. The distribution of deliverables featuring pulse crops among the various categories were similar between Canada and Australia. Crop management and protection composed 64 to 68% of the publications; breeding and genetics, 7%; end-use, 2 to 3%; and cropping systems and rotations, 21 to 26%. The following subsections will analyze key policies, research, and market developments in each of these four themes that stimulated diversification and intensification efforts in Canada and Australia.

3.2.1. Breeding research: development of alternative crops

The evolution of canola in Canada is unique in that researchers developed an edible crop from a non-edible rapeseed. Not surprisingly, breeding was the primary focus of 33 to 100% of the canola papers published prior to 1977 and 22% of papers published since 1971. Public policy played a critical role in stimulating the interest of rapeseed in Canada. During the Cold War in the mid-1950s, policy directed the Canadian National Research Council (NRC) to develop an edible rapeseed in response to the country's lack of a domestic source of edible oil and concern over food security (Busch et al., 1994). Research and development was particularly important in the initial efforts. For instance, the Canadian government invested C$18 million in canola research in the 1970s, which were comparable to maize research by the US government (Brewin and Malla, 2013). The first breeding program targeted Low Erucic Acid Rapeseed (LEAR) varieties after linking

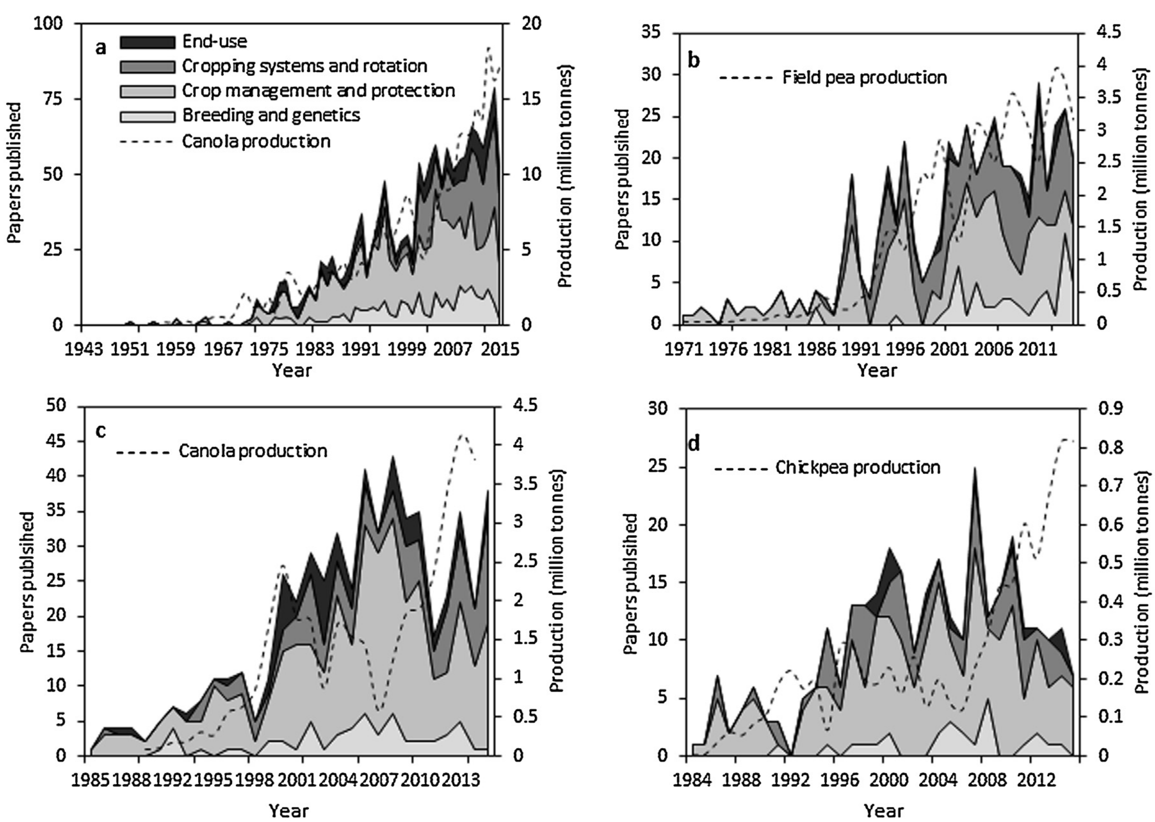

Fig. 5. Trends in Canada's production and published literature on (a) canola and (b) field pea and Australia's production of (c) canola and (d) chickpea. Identified literature themes included breeding and genetics, crop management and protection, cropping systems and rotation, and end-use.

eruric acid to heart disease. Later breeding programs focused on reducing the levels of sulfur-containing glucosinolates in the rapeseed meal (double-low). The impact of new varieties is evident: canola area expanded after the release of the first LEAR variety in 1970–1971, followed by the release of the first double-low variety and additional varieties with dramatically higher yields in 1984, 1993, and 2003 (Brewin and Malla, 2013). Globally, canola breeding has since entered an era of targeted agronomic improvements through private transgenic varieties (Gray et al., 2001).

In contrast to Canada, canola breeding and genetics research in Australia comprised 7 to 9% of published papers, which may be expected since recent innovation has largely been driven by private breeding companies which release and license new varieties (Salisbury et al., 2016). Early canola breeding programs in Australia were primarily focused on adapting varieties to existing cropping systems and climatic conditions following the introduction of poorly adapted germplasm from Canada (Salisbury et al., 2016). In the 1960s, public programs were largely focused on crop management and protection, such as the resistance to the Blackleg fungus (*Leptosphareia maculans*), which had devastated the fledgling industry; and later herbicide tolerant, double-low varieties adapted to Australia's short day winter-spring season (Salisbury and Wratten, 1999). In the late 1990s, the development of early maturing, herbicide tolerant varieties permitted the expansion of canola production in Australia's lower rainfall environments of Western Australia and South Australia (less than 350 mm per year) (Salisbury and Wratten, 1999).

3.2.2. Crop management and protection research: adaptation of alternative crops

The importance of crop management and protection for the adaptation of alternative crops is strongly reflected by the literature, which is the focus of 53–68% published papers. In Australia, improvements in canola agronomic practices led to increases in growers' yield and profits, including the amelioration of soil acidity, applications of sulfur fertilization, and improved pest management with knowledge being widely disseminated by the Canola Check crop monitoring and extension program (Stanley et al., 1999). However, wide adaptation of canola has been challenged by disease resistance and climatic conditions. For instance, Blackleg disease pressure on canola in higher rainfall areas and limitations in available water during the Millennium Drought (Marino, 2014) led to temporary declines in the extent of alternative crops within many agroecological zones throughout the 2000s (Kirkegaard et al., 2016). Currently, though most canola is grown in the medium to high rainfall zones of southern and southwestern Australia (Fig. 6) and is still considered more risky in the lower rainfall zones of the south and west (Hunt and Norton, 2011; Robertson et al., 2010) and northern-eastern wheat belt (Robertson and Holland, 2004), breeding and agronomic research continues to expand the areas sown to canola (Kirkegaard et al., 2016). In the low rainfall zones, juncea canola (*Brassica juncea*) has also been identified as an alternative, although crop establishment, marketing and improved canola types for low rainfall area have restricted adoption (Hunt and Norton, 2011).

Similarly, canola has also not successfully fit into all rotations across the Canadian agroecological zones. Since water availability is a major limitation of canola yields (Morrison et al., 2016), the expansion of canola has mostly been concentrated in the sub-humid, grey and black soil zones where it was adapted to the region's short, cool season (Padbury et al., 2002). Recent breeding efforts have focused on the earlier and longer flowering juncea canola, adapted to warmer drier environments (Bueckert and Clarke, 2013) but with variable success (May et al., 2010). Other efforts have focused on the performance of winter canola in the semi-arid region (Johnston et al., 2002).

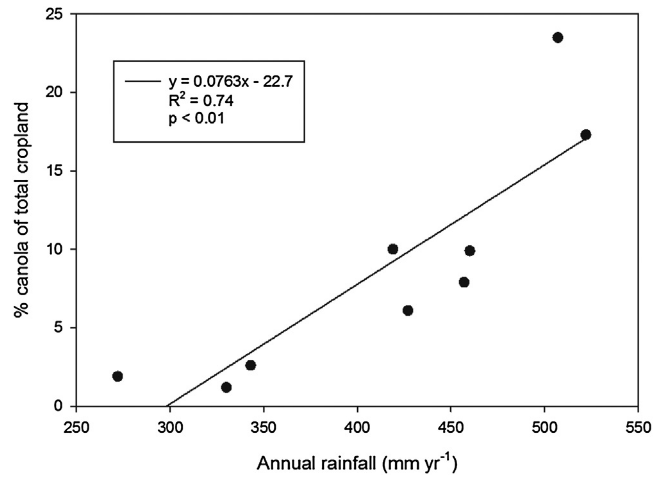

Fig. 6. Relationship between proportion of canola of total cropland and annual rainfall in the south and west GRDC regions of Australia.
Data source: GRDC 2007–2009 baseline agroecological zone surveys.

Efforts to expand pulse crops in Canada and Australia focused primarily on adaptation in specific environments. Prior to the 1970s, the production of field peas and lentils in Canada was primarily limited to the sub-humid province of Manitoba (Slinkard et al., 1990; McVicar et al., 2000). The Saskatchewan's Crop Development Centre, established in 1971, consisted of a multidisciplinary team focused on the expansion of economically viable alternative crops for Western Canada. Like canola, cool season pulses were identified by Prairie Regional Laboratory of the NRC as a domestic source of protein (Slinkard et al., 1990), which aimed to release of field pea and lentil varieties adapted to the drier environments of Western Canada (Slinkard et al., 1990; McVicar et al., 2000; Burnett, 2014).

Likewise, Australian research efforts focused on selecting adapted pulse varieties to suitable environments, and therefore the expansion of specific pulses have often been restricted to particular geographic regions (Greijdanus and Kragt, 2014). Early Australian pulse breeding programs initiated in 1950s led to the release of more than a dozen narrow-leaf lupin varieties adapted to acidic, gravely, deep sand and sandy loam soils (Hambin, 1987; Rees et al., 1994; Siddique and Sykes, 1997), which enabled the expansion of lupin across Western Australia in the 1980s (Hambin, 1987). Field pea and lentil were adapted to the low rainfall, Mediterranean environment of the southern states of Australia using landraces and germplasm made available through collaborations with international breeding programs (Siddique et al., 2013). In Australia's northern region, chickpea breeding programs utilized germplasm screened and developed at international centers, particularly for ascochyta blight (*Phoma rabiei*) tolerance, which reached epidemic levels in the late 1990s (Siddique et al., 2013). Recent higher prices led to the expansion of chickpea in the northern region. However, economic risk has been cited as an important constraint to the adoption of break crops in regions such as Western Australia (Ghadim et al., 2005; Robertson et al., 2010).

3.2.3. Cropping systems and rotation research: integrating alternative crops in rotations

Since 2000, cropping system-level research has been an increasing focus, particularly in Canada where rotational studies have averaged 31 to 38% of published papers. A critique of farm diversification in Canada reported that, despite crop diversification on aggregated national and regional levels (Zentner et al., 2002), on-farm diversity declined at a rate of 1% per year from 1994 to 2002 (Bradshaw et al., 2004). One possible explanation for this

finding was how diversity was measured. It is possible that the growers were participating in fewer market classes of crops rather than fewer types of grains as the authors differentiated among market classes in their diversity index (e.g. hard red spring wheat was considered separate from a soft white spring wheat and so on). Previous papers have grouped market classes together to analyze trends in types of grains, namely cereals, pulses, or oilseeds. However, a second reason may be that canola has been increasingly grown in shorter rotations with wheat (Smith et al., 2013). Canola area now makes up 86% of the total area sown to wheat in Canada which may be indicative of a two-year canola-wheat rotation, even though cropping system research recommends rotating canola every four years due to increased pressure of Blackleg in shorter rotations (Smith et al., 2013).

Nevertheless, farm-level diversification in the *semi-arid region* actually increased from 1994 to 2002 (Bradshaw et al., 2004), as the result of technological advances, such as herbicides and direct seeding, that facilitated the expansion of pulses in replacement of annual fallow (McVicar et al., 2000). The expansion of pulses in the semi-arid region has been attributed to the relatively better performance of pulse crops under severely water-stressed environments of the Canadian prairies (Angadi et al., 2008; Cutforth et al., 2009; Bueckert and Clarke, 2013), shallower rooting depth, and greater availability of residual deep water for the subsequent wheat or canola crops (Gan et al., 2009), much like the adaptation of pulse crops in Australia. By the late 1990s, research on pulse crops highlighted the rotational benefits of pulses to cereals (Miller et al., 2003) as a means to economically intensify crop rotations in Canada's brown soil, semi-arid zone. This is evidenced by the focus on field pea in cropping system research in 26% of the published papers (Fig. 5).

In Australia, cropping systems research has largely focused on the benefits of break crops (Norton et al., 1999; Kirkegaard et al., 2008; Seymour et al., 2012; Angus et al., 2015; Malik et al., 2015) and the persistent benefits of lupins and other pulses in crop rotations (Seymour et al., 2012; Angus et al., 2015; Malik et al., 2015), which increase profits within the economic limits of optimal area for break crops (Robertson et al., 2010). The emphasis on cropping systems is notable, constituting 18 and 21% of canola and chickpea papers, respectively. Current innovative canola research includes dual purpose (grazing and grain) of spring canola varieties in the medium rainfall zone (400 mm to 650 mm) (Kirkegaard et al., 2012; McCormick et al., 2012; Bell et al., 2014) and winter varieties in the >650 mm high rainfall zone (Sprague et al., 2014; Dove et al., 2015; Paridaen and Kirkegaard, 2015).

An important driver for cropping system-level research in Australia was the consolidation of narrowly-focused Australian commodity councils in 1989, followed by the formation of the GRDC for multiple crops and systems research. The GRDC is an independent but legally transparent entity responsible for the spectrum of grain research, development, and extension in Australia, which collects a mandatory check-off levy from grain sales matched with Federal Government funds, and largely drives continued investments in research of cereal and alternative crops. The influence of the GRDC is attested by their grower surveys, which claimed 70% of the 1200 growers had made informed practice changes influenced by their information (Watson and Watson, 2015).

3.2.4. End-use research: development of markets and market assess

The importance of commodity markets and end-use is illustrated with the expansion of canola in Canada, which was the focus of 12% of published papers. The canola market was developed in Canada under the management of the Canadian public sector (Phillips, 2000), and required coordinated efforts among federal agencies, commercial crushers, wheat pools, farmers, and universities (Anstey, 1986). Shortages of Asian and European rapeseed supplies during World War II led to the first Canadian commercial production of rapeseed in 1943. As a result, rapeseed production expanded until the price supports were eliminated in 1950 (Anstey, 1986). However, production resumed after the opening of rapeseed trade on Winnipeg Commodity Exchange in 1963. The development of a canola market was largely facilitated by the industry's ability to utilize existing resources along the full value chain (Busch et al., 1994). Growers employed wheat farming equipment without expensive modifications. Canola was transported on wheat rail lines subsidized by the Crowsnest Pass, stored in grain elevators, processed in World War II era rapeseed crushing facilities, and incorporated into established end products (e.g. margarine). Several key events helped mature the market: the formation of the Rapeseed Association of Canada in 1967, which later became the Canola Council of Canada (Brewin and Malla, 2013); the registration of canola in 1978; the granting of US Generally Recognized as Safe (GRAS) status in 1985; and the establishment of provincial commission check-off levy programs in 1990. Coinciding with the health claim issued by US Food and Drug Administration in 2006, canola met 50% of the cooking oil demand in Canada (Casseus, 2009).

The importance of favorable trade policy and market access is demonstrated by the expansion of pulses in Australia. In the early 1980s, research levies were not systematically collected for all pulse crops, market information was not readily accessible, and national statistics were not routinely collected (Hambin, 1987). The Grain Legume Research Council was established in 1985, proposed by the National Oilseeds and Protein Crops Committee of the Australian Wheat Growers Federation. Jointly with industry, the program developed a full-value chain research scheme funded by lupin and field pea levies and later chickpea. In the late 1980s, lupin production expanded rapidly due to the relative profitability of pulses to wheat and wool. Field pea, lentil, and chickpea production increased rapidly in response to international policy, which opened feed markets in Europe and food markets in India and Bangladesh (Rees et al., 1994; Siddique and Sykes, 1997). In 1995, pulses covered more than 2 million hectares, making up 10% of Australia grain production. At that time, production was anticipated to expand by more than 1 million hectares within the next decade (Siddique and Sykes, 1997). However, in the 1990s, lupin production in Western Australia began to decline in response to lower lupin prices, more herbicide resistance weeds, and the rise of canola and alternative pasture crops (Robertson et al., 2010). Chickpea cropping, on the other hand, has continued to expand in the northern regions of Australia driven by high prices. Chickpea area has quadrupled since 2004, and Australia was the largest exporter of chickpea in 2015.

3.3. Constraints to alternative cropping in the iPNW

Despite similar opportunities to effectively improve the agronomics and economics as has occurred in Canada and Australia, crop diversification in the inland Pacific NW (iPNW) has lagged behind other semi-arid regions of the world (Zentner et al., 2002; Cook et al., 2002; Conley et al., 2004; Kirkegaard et al., 2008). The iPNW has distinct agroecological classes defined by precipitation, temperature, and soils (Schillinger et al., 2008; Douglas et al., 1990; Huggins et al., 2014). For the last 125 years, eastern Washington and surrounding areas of Oregon and Idaho have been highly monocultured in a wheat- fallow system, making up 73% of harvested grain cropland, with cool season pulses in the wetter annual cropping areas providing some crop diversification. Fallow was traditionally used throughout to accumulate water and nitrogen and manage weeds. In 1910, field peas were introduced into the rotations to combat soil erosion that accompanied fallow

in the complex topography of the higher rainfall zones (Granatstein, 1992). From 1928 to 1943, field pea production expanded from 2 to 12% of harvested cropland. However, crop diversification ceased to expand as the availability of commercial fertilizers, chemicals, and government commodity programs supported the intensification of subsidized wheat (Granatstein, 1992). Since 1943, pulses have averaged nearly 5% of harvested cropland, and mostly concentrated in the annual cropping area.

The iPNW region is a unique rainfed cropping area in its general lack of oilseeds in crop rotations (Pan et al., 2016). In the 1970s, growers and researchers with federal support sought oilseed agronomic, economic, and processing opportunities in the iPNW (Divine et al., 1977) to build regional knowledge of oilseed production in the iPNW (Porter et al., 1981; Bettis et al., 1982; Kephart, 1986; Auld et al., 1993; Johnson and Lewis, 1995). Meanwhile, *Brassica* agronomy, breeding (Brown et al., 1995), and biodiesel engineering programs (Bettis et al., 1982; Peterson, 1984) were established at the University of Idaho. Despite research demonstrating the potential to develop and adapt improved winter and spring canola varieties, systemic economic and marketing constraints have limited commercial production of canola in the iPNW. However, upon enactment of legislation in 2006, Washington State public and private investments in oilseed processing facilities (Washington State House Bill 2775) stimulated a market demand for regionally grown oilseeds (Sowers and Pan, 2014).

3.3.1. Environmental constraints to crop diversification in iPNW

The diversity of environments and soils across the iPNW presents challenges to implementing wheat-oilseed-pulse cropping systems within each zone. In particular, the precipitation gradient and low proportion of precipitation received during the growing season combined with its extreme temperature range (-25 to 40 °C) makes the iPNW a unique dryland agricultural region (Pan et al., 2016). Opportunities for diversifying traditional cropping sequences include the substitution of (1) spring canola for the spring cereal in the annual cropping sequence, (2) winter/spring oilseed or pulse for wheat in the transitional sequence (fallow every three years) in an average precipitation year, or spring oilseed or pulse replacing fallow in a higher than average precipitation year, and (3) winter canola or pulse for winter wheat every fourth year in the dry grain-fallo`w zone

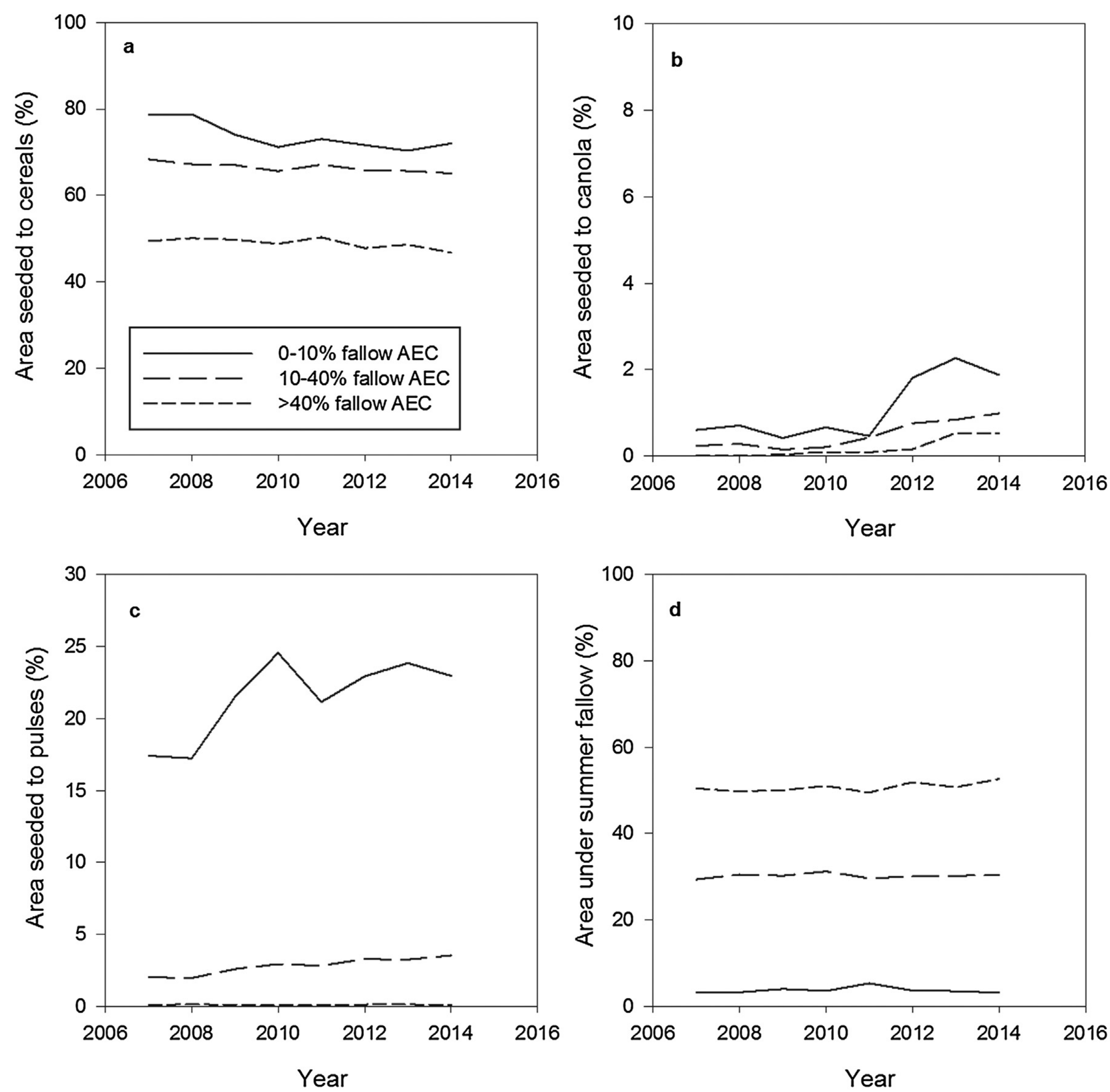

Fig. 7. Trends in (a) cereal, (b) canola seeded area, (c) pulse, and (d) fallow among the inland Pacific Northwest's annual cropping (0–10% fallow), intermediate (10–40% fallow), and grain-fallow (>40%) agroecological classes. Data.
Source: USDA NASS Cropland datalayer.

(annual fallow every other year). Warmer, wetter winters, as predicted, may expand future prospects for rotational options of alternative winter crops (Walden, 2014; Abatzoglou et al., 2015).

From 2007 to 2014, the increase in chickpea, canola, field pea, and fallow area came at the expense of wheat in the iPNW (Fig. 7). Multi-year geospatial analysis and interpolation of satellite images indicate that the agroecological classes of the iPNW are dynamic and can change geographically year-to-year (hence the distinction of class from zone), and growers altered their crop rotations from 2007 to 2014 in response to weather conditions (Huggins et al., 2014; Kaur et al., 2015), similarly to in Australia. The growers who practiced fallow once every three years were particularly responsive to weather conditions. Modeled climate projections, coupled with empirical data on how growers practice fallow in response to climate variability, predict an even greater fallow frequency among annual cropping (Kaur et al., 2015). A shift toward more fallow by annual crop growers could have major impacts on crop diversification. Oilseed and pulse crops are ten-fold more prevalent in annual cropping (Fig. 7b and c); and so on the one hand, an increase in fallow may result in a further cereal specialization. On the other hand, innovative growers are beginning to adapt agronomic management to improve canola adaptation into wheat-fallow systems (Pan et al., 2016), while those who have traditionally cropped annually could potentially bring the skills, knowledge, and experience to best fit alternative crops into a less intensified rotation. Cropping system research is continually striving to identify practices to conserve water and develop adapted spring and winter varieties.

3.3.2. Economic and policy constraints to crop diversification in iPNW

Rotational enterprise budgets indicate that a wheat-fallow rotation was more profitable than the canola-fallow-wheat-fallow when based on the minimum federal protections in 2013 (Table 1). However, rotating winter canola became hypothetically profitable under one or more of the following conditions: (1) winter wheat yields in rotation with canola increased by 1000 kg ha^{-1}, (2) winter canola yields were greater than 100% of the baseline insurance coverage, and/or (3) canola prices exceeded \$0.60 kg^{-1} while wheat prices remained at \$0.21 kg^{-1}. In a three-year rotation with spring canola, these conditions for rotating canola profitably were theoretically more easily met (Table 2). Rotating spring canola instead of spring wheat became profitable when (1) winter wheat yields increased by 670 kg ha^{-1}, (2) winter canola yields were greater than 35% of the baseline insurance coverage, and/or (3) canola prices exceeded \$0.46 kg^{-1} when spring wheat prices remained at \$0.19 kg^{-1}.

It is widely acknowledged that subsidies distort markets (Anderson et al., 2013). Historically, the federal government of the USA has intervened in grain markets by imposing price floors, price ceilings, and subsidies. The goal of such government intervention is to stabilize farm income and ensure that growers can manage economic risk, despite necessitating governments to mediate issues of oversupply and price decline. In the USA, agriculture subsidies have taken the form of direct and indirect payments to farmers, while federal policies have established price ceilings and floors. Prior to 2008, the US agricultural support programs favored a selected number of crops, including maize (*Zea mays*), wheat, soybean, and cotton (*Gossypium hirsutum*). As a result, lack of access to federal financial assistance and risk management programs are historic barriers to alternative crop adoption in the US. In 2008, the Food, Conservation, and Energy Act (2008 Farm Bill) gave US canola producers access for the first time to marketing loans, direct payments, counter-cyclical payments, average crop revenue election payments, and subsidized crop and revenue insurance. Further changes were enacted in the US Agricultural Act of 2014. Among the most significant changes were the elimination of direct payments, the counter-cyclical price program, and the average crop revenue election program.

In 2014, the US government increased the funding of federal crop insurance programs. Canola and pulses are among the 100 crops to qualify for subsidized crop insurance policies for yield and crop revenue protection (Chite, 2014). However, the availability of federal crop insurance is administered at a county level. For instance, in Washington state, revenue protection is available for

Table 1

Sensitivity analyses† of winter wheat yields, prices, and lease structure effects on profitability for a grower in Adams County, WA, selecting either a winter canola-fallow-winter wheat-fallow rotation (WC-F-WW-F) or winter wheat-fallow rotation (WW-F-WW-F). (For interpretation of the references to colour in this Table legend, the reader is referred to the web version of this article.)

Sensitivity analysis of winter wheat yield effects on relative rotation profitability																
		WW yield in WC-F-WW-F rotation (kg ha^{-1})														
WW yield in WW-F-WW-F rotation (kg ha^{-1})		*1843*	*1843*	2011	2179	2346	2514	2681	2849	3017	3184	3352	3519	3687	2855	4022
	1843	*(20)*	*(20)*	(16)	(12)	(8)	(3)	1	5	9	13	17	22	26	30	34
	1843	*(20)*	*(20)*	(16)	(12)	(8)	(3)	1	5	9	13	17	22	26	30	34
	2011	(28)	(28)	(24)	(20)	(16)	(11)	(7)	(3)	1	5	9	14	18	22	26
	2179	(36)	(36)	(32)	(28)	(24)	(19)	(15)	(11)	(7)	(3)	1	6	10	14	18
	2346	(45)	(45)	(41)	(37)	(33)	(28)	(24)	(20)	(16)	(12)	(8)	(3)	1	5	9
	2514	(54)	(54)	(50)	(46)	(42)	(37)	(33)	(29)	(25)	(21)	(17)	(12)	(8)	(4)	0
Sensitivity analysis of winter crop price effects on relative rotation profitability																
		WC price in WW-F-WC-F rotation (\$ kg^{-1})														
WW price in WW-F-WW-F rotation (\$ kg^{-1})		*0.38*	*0.38*	0.40	0.42	0.44	0.46	0.49	0.51	0.53	0.55	0.57	0.60	0.62	0.64	0.66
	0.22	*(21)*	*(21)*	(18)	(17)	(15)	(12)	(10)	(8)	(6)	(3)	(1)	2	4	6	9
	0.22	*(21)*	*(21)*	(18)	(17)	(15)	(12)	(10)	(8)	(6)	(3)	(1)	2	4	6	9
	0.23	(23)	(23)	(20)	(19)	(17)	(14)	(12)	(10)	(8)	(5)	(3)	(0)	2	4	7
	0.23	(25)	(25)	(23)	(21)	(19)	(17)	(15)	(12)	(10)	(7)	(6)	(3)	(0)	2	4
	0.24	(27)	(27)	(25)	(23)	(21)	(19)	(17)	(14)	(12)	(9)	(8)	(5)	(2)	(0)	2
	0.25	(29)	(29)	(27)	(25)	(23)	(21)	(19)	(16)	(14)	(11)	(9)	(7)	(4)	(2)	0
	0.26	(32)	(32)	(29)	(28)	(26)	(23)	(21)	(19)	(17)	(14)	(12)	(9)	(7)	(5)	(2)

†Entries in the table were calculated as profit (\$) from the rotation with canola minus the profit from the winter wheat rotations. Numbers in red indicate that the winter wheat-fallow rotation is more profitable, whereas black numbers indicate that the winter canola-fallow-winter wheat-fallow is relatively more profitable. Profitability is based on 70% coverage of county base yields and prices for winter wheat and canola (in italics). Numbers in the top rows and first columns of the table (in bold) represent changes in winter wheat yields or prices in rotation with canola and winter wheat rotation, respectively. As an illustration, in the top section, at base winter wheat yields of 1843 kg ha^{-1}, winter wheat yields in the canola rotation have to be at least 2681 kg ha^{-1} for the canola rotation to be relatively more profitable under the assumed output and input prices.Data source: USDA RMA and Washington's Rotational Enterprise Budget tool.

Table 2
Sensitivity analyses of winter wheat yields, prices, and lease structure effects on profitability for a grower in Columbia County, WA, selecting either a winter wheat-spring canola-fallow rotation (WW-SC-F) or winter wheat-spring wheat-fallow rotation (WW-SW-F) (For interpretation of the references to colour in this Table legend, the reader is referred to the web version of this article.).

Sensitivity analysis of winter wheat yield effects on relative rotation profitability

WW yield in WW-SW-F rotation (kg ha^{-1}) \ WW yield in WW-SC-F rotation (kg ha^{-1})	*3620*	*3620*	3754	3888	4022	4156	4290	4424	4558	4692	4827	4661
3620	(9)	(9)	(7)	(4)	(2)	(0)	2	4	7	9	11	13
3620	(9)	(9)	(7)	(4)	(2)	(0)	2	4	7	9	11	13
3754	(11)	(11)	(9)	(7)	(5)	(2)	(0)	2	4	7	9	11
3888	(13)	(13)	(11)	(9)	(7)	(4)	(2)	(0)	2	4	7	9
4022	(16)	(16)	(13)	(11)	(9)	(7)	(5)	(2)	(0)	2	4	7
4290	(18)	(18)	(16)	(14)	(12)	(9)	(7)	(5)	(2)	(0)	2	4
4424	(20)	(20)	(18)	(16)	(14)	(11)	(9)	(7)	(4)	(2)	(0)	2

Sensitivity analysis of spring crop yield effects on relative rotation profitability

SW yield in WW-SW-F rotation (kg ha^{-1}) \ SC yield in WW-SW-F (kg ha^{-1})	*899*	*899*	930	1041	1153	1265	1376	1488	1600	1712	1823	1935	2047	2159
1740	(8)	(8)	(8)	(4)	(1)	3	6	9	13	16	20	23	26	30
1740	(8)	(8)	(8)	(4)	(1)	3	6	9	13	16	20	23	26	30
2011	(10)	(10)	(9)	(6)	(2)	1	5	8	11	15	18	22	25	29
2212	(13)	(13)	(12)	(8)	(5)	(1)	2	5	9	12	16	19	22	26
2346	(16)	(16)	(15)	(11)	(8)	(4)	(1)	2	6	9	13	16	19	23
2547	(18)	(18)	(17)	(14)	(10)	(7)	(4)	(1)	3	7	10	13	17	20
2681	(21)	(21)	(20)	(17)	(13)	(10)	(6)	(3)	0	4	7	11	14	18
2883	(24)	(24)	(23)	(20)	(16)	(13)	(9)	(6)	(3)	1	4	8	11	15

Sensitivity analysis of spring crop price effects on relative rotation profitability

Wheat price in WW-SW-F rotation (\$ kg^{-1}) \ Spring canola price in WW-SC-F rotation (\$ kg^{-1})	*0.38*	*0.38*	0.40	0.42	0.44	0.46	0.49	0.51	0.53	0.55	0.57	0.60	0.62	0.64	0.66
0.19	(5)	(5)	(4)	(2)	(0)	1	3	5	6	8	10	11	13	15	17
0.19	(5)	(5)	(4)	(2)	(0)	1	3	5	6	8	10	11	13	15	17
0.20	(7)	(7)	(5)	(3)	(2)	(0)	2	3	5	7	8	10	12	13	15
0.21	(9)	(9)	(7)	(5)	(3)	(2)	(0)	2	3	5	7	8	10	11	13
0.22	(10)	(10)	(8)	(6)	(5)	(3)	(1)	1	2	4	6	7	9	10	12
0.23	(11)	(11)	(10)	(8)	(6)	(5)	(3)	(1)	0	2	4	5	7	9	11
0.24	(13)	(13)	(11)	(9)	(8)	(6)	(4)	(3)	(1)	1	2	4	6	7	9
0.25	(14)	(14)	(12)	(11)	(9)	(7)	(6)	(4)	(3)	(1)	1	3	4	6	8

†Entries in the table were calculated as profit (\$) from the rotation with spring canola minus the profit from the spring wheat rotations in. Numbers in red indicate that the rotation with spring wheat is more profitable, whereas black numbers indicate that the rotation with spring canola is relatively more profitable. Profitability is based on 70% coverage of county base yields and prices for winter wheat and canola (in italics). Numbers in the top rows and first columns of the table (in bold) represent changes in spring crop yields, winter wheat, yields or prices in rotation with spring canola and spring wheat rotation, respectively. As an illustration, in the top section, at base winter wheat yields of 3620 kg ha^{-1}, winter wheat yields in the canola rotation have to be at least 4290 kg ha^{-1} for the rotation with spring canola to be relatively more profitable under the assumed output and input prices.Data source: USDA RMA and Washington's Rotational Enterprise Budget tool.

wheat in 29 counties; 13 for canola; 11 for field peas; eight for lentils; four for chickpeas; and none for camelina and safflower (USDA RMA, 2016b). The availability of crop insurance can be critical for growers operating on a loan since insurance might be a requirement to attain financing. Furthermore, land leasing contracts are renewed every one to five years, and growers may sow "less risky" traditional crops to appease absentee land owners.

Policies that focus on crop insurance for a specific commodity can negatively affect diversification, and many substitute for ecological risk management that could be attained through crop diversification (Di Falco et al., 2014) while risk reduction of single crop insurance models may not carry over to a multi-crop schemes (Woodard et al., 2010). In 1994, the reformation and expansion of US federal crop insurance increased crop specialization due to less exposure to risk (O'Donoghue et al., 2009). For instance, in the early 1990s, rotation diversification and intensification were greater on the Canadian side of the border than the US side in the Northern Great Plains, despite similarities in soils, climatic, and topographic characteristics. Differences in crop diversity along the border were attributed to USA policy encouraging growers to maintain base acreage, while high canola to wheat price ratios (Smith and Young, 2003) coupled with whole-farm, income-stabilization programs encouraged diversity in Canada. In 2014, the US began the transition to a whole farm, income-stabilization insurance approach, which is designed to diversify crop options. However, it is important to acknowledge that, while the whole farm approach increases options for diversity, it too does not necessarily lead to diversification particularly when wheat market prices are high. For example, Canada has not consistently been more diverse than the US when wheat prices are high relative to canola (Smith and Young, 2003).

3.3.3. Social constraints to crop diversification in iPNW

The REACCH producer surveys conducted in 2012 illustrate that producers surveyed in the iPNW perceived greater economic than environmental risk when faced with future uncertainties associated with climate change (Fig. 8). The majority of growers across all agroecological classes anticipated little to no changes in their crop rotation due to projected climate change, whereas less than 5% of all growers expect major changes (Table 3). However, the distribution of perceptions differed among the agroecological classes. A greater proportion of growers (70%) practicing fallow once every three years foresaw small to moderate changes in their rotations amidst a changing climate, in comparison to annual cropping (54%) and grain-fallow (53%). Furthermore, growers practicing grain-fallow were less likely to anticipate moderate changes (9%) than growers in the annual cropping (16%) and transition (25%) areas. These attitudes are reflected by the USDA

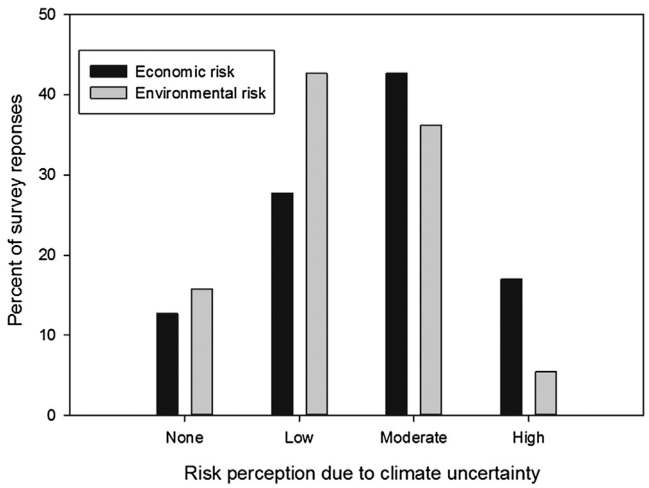

Fig. 8. Economic and environmental risk perception of surveyed growers (n = 900) due to future climate uncertainty. Data.
Data source: 2012 REACCH producer surveys.

Table 3
Perceived changes in crop rotation based on anticipated changes in climate among surveyed growers in the inland Pacific Northwest's agroecological classes based on fallow intensity.

	Frequency of responses	Proportion of responses%
0-10% fallow		
No change	118	42
Small change	106	38
Moderate change	49	17
Big change	9	3
11–40% fallow		
No change	33	26
Small change	57	45
Moderate change	32	25
Big change	5	4
>40% fallow		
No change	69	44
Small change	67	43
Moderate change	15	10
Big change	5	3

Data source: 2012 REACCH producer surveys.

NASS satellite survey data which demonstrate a shift in cropping practices year-to-year, particularly for the growers practicing fallow every three years.

The importance of economics is reflected by the growers surveyed at the 2012 and 2013 Washington State oilseed workshops, who reported that market price was the major barrier to oilseed adoption, whereas less than half of the growers ranked experience or agronomic knowledge as the major constraint (Table 4). This is particularly important since the iPNW rotational enterprise budgets illustrate that alternating canola with wheat and fallow is not always profitable, and the profitability of canola was contingent on favorable canola yields and prices, as well as an increase in winter wheat yields in rotation with canola. More than half of the growers surveyed in the oilseed workshops did report their subsequent winter wheat yields increased by more than 10%, which may increase profitability relative to the wheat monoculture depending upon the minimum production levels.

Two recent cropping trends highlight the importance of commodity prices, gross returns, and access to markets. From 2007 to 2014, canola area increased by three-fold in the annual cropping region and 100-fold in the grain-fallow region driven by high price ratios, access to regional markets, and availability of adapted winter varieties in the low rainfall zone (O'Connell, 2012). Chickpea area increased by two to four-fold across all agroecological classes in response to high chickpea to wheat price ratios,

Table 4
Clicker survey responses from Washington Oilseed Cropping Systems project's grower workshops in 2012 and 2013.

		2012	2013
Grower attendees		36% n = 58	40% n = 103
Grown oilseed in previous 3 years		73% n = 30	74% n = 57
Likely to grow winter canola in the future		77% n = 25	58% n = 59
Limitations of growing canola			
	Market price/economics	63%	50%
	Experience	14%	20%
	Agronomic knowledge	14%	18%
	Too many residual herbicides	8%	6%
	Government programs	2% n = 59	6% n = 103
Perceived rotational benefits			
Root System		16%	NA
Increased Yield		45%	NA
Pest Management		22%	NA
Water Management		16% n = 57	NA
Reported increase in winter wheat			
None		0%	5%
0–5%		0%	0%
5–10%		36%	20%
10–20%		23%	39%
Over 20%		27%	14%
Don't know		14% n = 22	23% n = 44

NA = Not available.

relatively higher returns per hectare, and an increase in domestic demand (Ellis, 2014). However, the iPNW is unique in its high wheat profitability, in which canola and chickpeas were the only competitive alternative crops to wheat in recent years (Fig. 9), which is contrasted to the competitiveness of wheat in Canada during the wheat glut of the 1980s. Since 2014, the canola area in the iPNW has not increased as projected, which has been attributed partially to market instability associated with bankruptcies and ownership turnover of Washington State's crushing facilities (Pihl, 2013; Sowa, 2013).

4. Conclusions and recommendations

In Canada and Australia, initial public investments in multidisciplinary research and industry infrastructure was essential to integrate alternative crops into existing cropping systems and develop markets. Early research programs were focused on breeding, agronomy, and end-use to develop economically viable alternative crops to wheat adapted to specific agroecological regions. Ultimately, the success of alternative crops was dependent upon market development, involving grower groups, expansion of handling and processing facilities, industry representation, levy systems, favorable trade policy, access to markets, and establishing grading standards. In the iPNW, a lot of these conditions are met. The government has invested heavily in developing oilseed crushing and processing facilities, as well as multidisciplinary programs to encourage crop diversification. A wealth of genetic materials are available for adapting oilseed and pulse crops to the region's unique environment for spring, winter, and perennial varieties. Regional oilseed and pulse markets are prevalent, with opportunities to expand into niche markets with special traits. Washington State has commissions in place that collect pulse and oilseed levies to fund research, expand markets, and engage in policy.

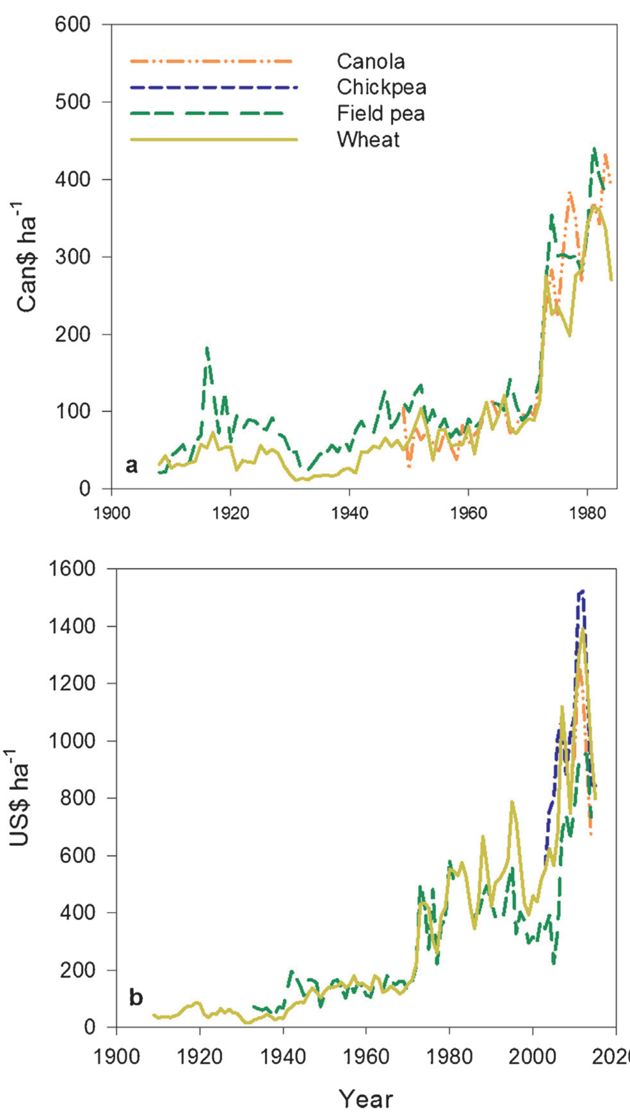

Fig. 9. Gross returns per hectare of crops in (a) Canada during early diversification efforts and (b) in the iPNW to recent year. Data.
Data source: Statistics Canada and USDA NASS Quickstat database.

Cropping trends in Canada and Australia indicate that finding a fit for alternative crops within existing cropping systems is very important. In Canada and Australia, canola and pulse crops were best fit in distinctly different agroecological zones. In the iPNW, a similar scenario may be envisioned, with the potential of winter canola and field peas in the grain-fallow region; and spring canola and chickpeas in more intensified rotations. However, a successful alternative crop in the semi-arid region of the iPNW must not only be agronomically feasible but economically competitive with wheat, which has been adapted to the most water-limited environments in the iPNW (<300 mm of annual precipitation). The high profitability of the iPNW wheat-based systems is a significant distinction, in which wheat growers were not seeking alternative crops in response to low wheat revenue or quotas like in Canada and Australia. The economic importance of cereals commercially in the region is reflected by the budget of the Washington Grain Commission, which allotted $2.1 million to further wheat research in Washington State for 2015/2016. Therefore, the most apparent opportunity for diversification in the iPNW is to adopt (1) an entire crop rotation approach to economics to capture relative commodity prices, yield stability, and effects of the break crop on the subsequent winter wheat, (2) income-supported, whole farm risk management risk management, and (3) the formation of state and regional multi-commodity groups that include break or alternative crops along with cereal grain crops.

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